8th Int. Symp. "Nanostructures: Physics and Technology"
St Petersburg, Russia, June 19–23, 2000

Photoelectronic properties of InAs/GaAs nanostructures with combined quantum well and quantum dot layers grown by Metal-Organic Vapor Phase Epitaxy

I. A. Karpovich†, B. N. Zvonkov§, *D. O. Filatov*‡, S. B. Levichev†, N. V. Baidus§ and S. M. Nekorkin§

† University of Nizhni Novgorod, 603600 Nizhni Novgorod, Russia
‡ Research and Educational Center for Scanning Probe Microscopy, University of Nizhni Novgorod, 603600 Nizhni Novgorod, Russia
§ Physical-Technical Research Institute, University of Nizhni Novgorod, 603600 Nizhni Novgorod, Russia

Abstract. Combination of quantum well (QW) and QD layers in the GaAs/$In_xGa_{1-x}As$ nanostructures obtained by MOVPE result not only in well known "red shift" of the QD PL spectrum, but also to splitting of the PL spectrum and of the photosensitivity spectrum of the QW. "Red shift" of one of these spectral features relative to the other is explained by diffusion of In from the QDs to the QW at their heterointerface.

GaAs/$In_xGa_{1-x}As$ nanostructures with separate quantum wells (QWs) and quantum dots (QDs) have been studied well to the present time. Recently studies of the nanostructures with QD/QW combined layers have been begun [1, 2]. It is expected to observe a number of corporate effects due to interaction of the QD and QW layers: redistribution and relaxation of elastic strains, intermixing of the components, hybridization of energy spectra of QD and QW, etc. All of the above can influence on the morphology and energy spectrum both of QD and QW and, in turn, on the their electronic properties. In these structures photoluminescence and lasing in the 1.3 μm band were obtained, which is important for optoelectronics [3]. Probably it is possible to achieve the next transmittance window at 1.5 μm. Decreasing of the ground state transition energy in a QD was explained by relaxation of the elastic strain [1] or by alloy decomposition and In segregation [2].

In this work, we investigated the surface morphology, photoluminescence (PL), and capacitive photovoltage (CPV) spectra of GaAs/$In_xGa_{1-x}As$ nanostructures with combined QD/QW layers of various types, grown by Metal-Organic Vapor Phase Epitaxy (MOVPE).

The nanostructures were grown on semi-insulating GaAs (001), misoriented by 3° towards [110]. n-GaAs ~0.8 μm buffer layers were grown at 600°C. Then temperature was decreased down to 530°C and InAs QD layer followed by $In_xGa_{1-x}As$ QW layer ($x \sim 0.2$, $d \sim 5$ nm) was deposited. In other series these layers were deposited in the inverse sequence. When growing the QDs trimethyl indium and arsine were introduced into the reactor alternatively for 6 and 4 s respectively with the 4 s intervals between the cycles. Total number of the cycles was up to 10, which results in the InAs nominal thickness of 1.5 nm (~5 monolayers (ML)). The structures both with and without 15 nm GaAs cap layer for optical and morphological investigations respectively were grown. Morphology of the QD layers was studied by Atomic Force Microscopy (AFM) using TopoMetrix 'Accurex' TMX-2100 AFM in contact mode. PL spectra were measured at 77 K and CPV spectra — at 300 K using the technique described in [4].

According to AFM data, when isolated InAs layers are grown on the GaAs surface, the InAs clusters with 45–50 nm base and 6–10 nm height are formed. Their surface density is $\sim 10^{10}$ cm^{-2} [5]. These parameters are close to the ones reported for the QDs grown

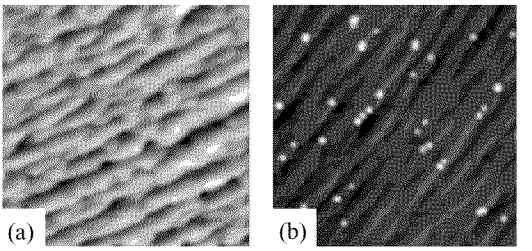

Fig. 1. AFM images of the surface of nanostructures: (a) QW/QD, (b) QD/QW.

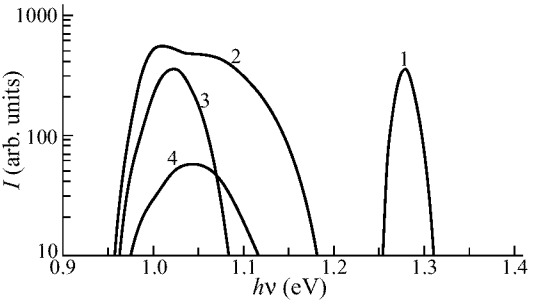

Fig. 2. Photoluminescence spectra (77 K) of the nanostructures: 1—QW, 2—QD, 3—QW/QD, 4—QD/QW.

by molecular beam epitaxy (MBE) in [1]. For rather large fraction of In in the QDs PL peak from QD shifts to lower energies down to 0.97 eV (77 K). The corresponding CPV peak shifts down to 0.9 eV (300 K). In the nanostructures grown by MBE such shift was achieved only by deposition of an additional QW layer over the QDs [1, 2]. High PL intensity comparable to the one of QW indicates the crystal structure of the QDs to be perfect enough. Such properties of the QDs grown by AP MOCVD can be explained by assuming formation of graded composition transient region around a QD originating from diffusion of In into GaAs playing a role of the external QW.

As the ground transition energy in the QD is considerably less than the one in the QW, and as an exciton generated by photoexcitation in the QW have enough time to relax to the QD ground state before recombination so PL from QDs only can be observed at low excitation levels. In contrary, in the CPV spectrum that represents the optical absorption spectrum all over the quantizied states it is possible to observe all quantum-dimensional layers [4]. However, because the surface density of QDs was rather small ($< 10^{10}$ cm^{-2}) it was sometimes difficult to resolve the QD photosensitivity above the impurity background due to the deep levels HL1 and EL2 in the substrate. Nevertheless, the InGaAs QW and the wetting layer were always well resolved. So the methods of PL and CPE appear to be complimentary allowing to resolve the objects of both types.

The morphology of combined QD/QW layers depends on consequence (order) of deposition. When depositing the QW onto the QDs (QW/QD) QDs are partly seen through the QW layer (Fig. 1(a)). Deposition of QW depressed coalescence of nanoclusters. In the QD/QW layer coalescence is stronger resulting in formation of big clusters and in decreasing the concentration of QDs (Fig. 1(b)). Tendency to the formation of groups of 2–3 clusters preceeding confluence of them is seen up. It should be noted that morphology of the QD/QW layers with a cup layer differs substantially from the one of the surface dots.

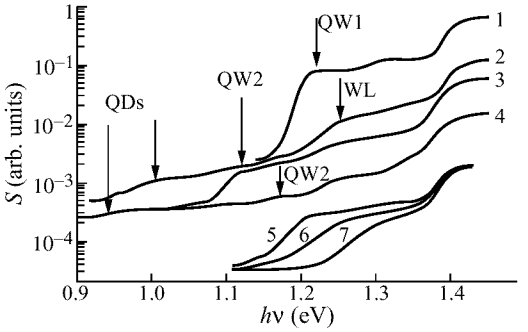

Fig. 3. CPE spectra of the nanostructures with the covered (1–4) and surface (5–7) quantum layers: 1, 7—QW, 2—QD, 3, 5—QW/QD, 4, 6— QD/QW.

Shift of the QDs' PL peak to lower energies by 30–40 meV compared to the one in the single QD layer always takes place in the QW/QD nanostructures of both types (Fig. 2). It should be noted that such shift was much less than in the structures obtained by MBE [1, 2].

In the CPV spectrum of the QDs (Fig. 3, curve 2) the CPV edges from QDs at ~0.98 eV and from wetting layer at ~1.23 eV are seen. In the structures with $In_xGa_{1-x}As$ QW ($x \sim 0.2$, the well width ~5 nm) the QW band has a sharp step near 1.2 eV (curve 1). In the QW/QD nanostructures a weak band from QD with threshold 0.94 eV is seen and its location at 300 K agrees with the PL peak position at 77 K (1.022 eV). In all the spectra of the combined layers the effects of splitting and of "red shift" of the QW band compared to the one of a single QW (QW_2 and QW_1 at ~1.1 and 1.2 eV respectively on curve 3) were observed. The band QW_1 is likely from initial QW between the QDs. Its integration with significantly much narrower but much deeper QW from InAs wetting layer results in disappearing of the wetting layer subband and in some shift of the QW subband as a result of the QW broadening and of change of the well potential shape. However, this effect could not explain the shift as much as by 0.1 eV. Probably it is due to the parts of QW covered by QD. Shift to lower energies can be explained by diffusion of In from the QDs to the QW which can reduce the effective gap of the latter. Effect of the QW broadening in the QD/QW combined layer is also seen (curve 4) but in this case it is less expressed and the "red shift" of QW is smaller.

Similar results were observed in the combined QW/QD layer without a cup layer (Fig. 3, curves 5–7). Bigger value of "red shift" in the QW/QD than in the QD/QW can be explained by absence of In diffusion from the QW to the matrix.

Acknowledgements

This work was supported by Program "Physics of Solid-state Nanostructures" (99-1141), by Russian Ministry of Education (97-7.1-204), by "Universities of Russia" Program, and by CRDF (BRHE Program, REC-001).

References

[1] K. Nishi, H. Saito, S. Sugou, J-S. Lee, *et al.*, *Appl. Phys. Lett.* **74**, 1111 (1999).
[2] B. V. Volovik, A. F. Caculnikov, D. A. Bedarev, *et al.*, *Fiz. Tekh. Poluprov.* **33**, 990 (1999).
[3] A. R. Kovsh, A. E. Ghukov, N. A. Maleev, *et al.*, *Fiz. Tekh. Poluprov.* **33**, 1020 (1999).
[4] I. A. Karpovich and D. O. Filatov, *Fiz. Tekh. Poluprov.* **30**, 1745 (1996).
[5] I. A. Karpovich, D. O. Filatov, S. V. Morozov, *et al.*, *Izv. Akad. Nauk, Ser. Fiz.* **63**, 331 (2000).